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PLASMA ETCHING METHOD HAVING PULSED SUBSTRATE ELECTRODE POWER

The present invention relates to a method for etching patterns in an etching body using a plasma according to the definition of the species of the main claim.

Background Information

Anisotropic plasma etching methods are known, for example, from DE 197 06 682 A1 or DE 42 41 045 C2, in which, in each case, a plasma of neutral radicals and electrically charged particles is produced via a high-density plasma source, the particles being accelerated by a bias voltage source in the direction of a substrate electrode carrying the wafer to be processed. In this context, a directed etching process is achieved by the preferential direction of the incident ions.

Furthermore, high-frequency generators having a carrier frequency of 13.56 MHz are typically used as the bias voltage source that produces the electrical voltage for accelerating the ions from the plasma in the direction of the substrate electrode. In this context, the high-frequency generator is adjusted by an LC network ("matchbox") to both the impedance of the substrate electrode and the plasma that is in contact with the substrate electrode.

Furthermore, under consideration of a good mask selectivity, i.e., the ratio of the silicon etching rate to the etching speed of the masking layer, it is already known to select the high-frequency power on the substrate electrode to be relatively low to keep the ion-supported mask removal as minimal as possible. Typical power values are between 5 watts and 20 watts, so that the energy of the ions inciding on the substrate surface is usually several units of 10 eV.

It is true that such low ion energies are advantageous with respect to the mask selectivity. However, as a result, the incident ions can also have a relatively significant degree of scatter with respect to their direction and can partially deviate from the desired, vertical incidence or can be slightly deflected, i.e., their directionality is low. Such deviations in the directionality of the incident ions then correlates to more difficult profile verification of the produced etching profile. Viewed in terms of the directionality of the ion current, high ion acceleration, i.e., high ion energy, would, therefore, be desirable, which, however, conflicts with the necessary mask selectivity.

Furthermore, charging effects often occur on the boundary layer silicon dielectric when using high-density plasmas having low-energy ion action on a substrate in response to impacting upon an etch stop of dielectrics (buried oxides, lacquer layers, etc.). Profile imperfections in the silicon resulting therefrom are referred to as notching on the dielectric interface.

At the same time, as the ion energy increases, so does the danger of so-called "grass formation" on the etching ground, i.e., the process window for a reliable etching process without grass formation is limited. In this context, "grass formation" refers to the nonuniform etching of the etching ground while forming a plurality of closely adjoining points, which take on the shape of grass.

To achieve this objective, the applications DE 199 33 842.6 and DE 199 19 832.2 already proposed pulsing the high-frequency a.c. voltage, which is used for producing the substrate bias, i.e., for producing the substrate electrode power to be coupled into the substrate to be etched, and at the same time, selecting the ion energy to be higher during the high-frequency impulses than for continuous wave operation.

However, during this pulse control operation, it is observed that an effective suppression of the notching is first achieved in response to relatively long interval times of 0.1 ms to 1 ms between the applied high-frequency impulses. If the pulse intervals are shortened to under 0.1 ms, notching occurs more frequently and cannot be suppressed by increasing the peak pulse power and correspondingly shortening the pulse duration.

Moreover, for long interval times of 0.1 ms to 1 ms, the process window for a reliable process, i.e., a grass-free etching ground, narrows in response to the pulse time being shortened with a corresponding increase in the peak pulse power, i.e., the etching process becomes increasingly notch-resistant, but the suppression of a grass-free etching ground becomes increasingly smaller. To date, this requirement for a "notch-resistant" process, therefore, conflicts with a "grass-resistant" process.

In this context, the process window refers to process parameter ranges suitable for implementing an etching process, which is reliable in the explained manner, in particular with respect to process pressure, substrate electrode power, plasma power, and gas flows, as well as, in some instances, the cycle times for alternating etching cycles and passivation cycles.

On the whole, in the known methods under the marginal conditions of a "grass-free" etching ground and a sufficient suppression of "notching," the employable high-frequency peak pulse powers and, as such, the ion energies, i.e., the directionality of the ion incidence, is, therefore, restricted, thereby resulting, to date, in the process window, i.e., the usable process parameters, being restricted in an undesired manner.

Due to the grass formation, this restriction of the process window has a particularly disruptive effect when high-rate

etching processes are to be carried out, since, as such, the range of allowable process pressures is restricted in an upward direction. On the other hand, it is exactly high pressures, high gas flows, and high plasma powers at the inductive source that are advantageous for achieving high etching rates.

Summary of the Invention

In comparison with the related art, the plasma etching method according to the present invention has the advantage that with this method, the pulse times and interval times of the coupled, high-frequency-pulsed high-frequency power can be significantly shortened, and pulse operation having a high repetition rate in the 100 kHz range can be implemented.

At this high repetition frequency, the peak pulse power can now also be advantageously increased or scaled up in inverse proportion to the mark-to-space ratio.

At the same time, in addition to the notching (notching effects) being effectively suppressed, a very stable and robust process is achieved that does not have a tendency to form "grass" on the etching ground in response to the process parameters being varied within a wide process window.

Furthermore, in the method according to the present invention, very high-frequency peak powers can now be used for accordingly short pulse durations, i.e., an accordingly small mark-to-space ratio and/or pulse duty factor. Advantageously, the result is a correspondingly high ion energy of typically 50 eV to 1000 eV, which is associated with very good directionality of the ion incidence.

In this context, one takes advantage of the fact that, in response to using short pulses having a high rate of repetition, the time averaging of the power values takes place

over a tight sequence of short-time pulses from which every individual pulse represents only one relatively low energy input to the etching body. On the whole, this leads to a high level of process stability.

In opposition to the relatively long pulses having relatively long intervals in which the energy is already so high in a single pulse that interference effects occur in the electrode-plasma interaction during one single pulse, it is advantageously no longer observed in the method according to the present invention that shortening the pulse durations and correspondingly increasing the peak pulse power requires an increase in the average power necessary for etching input into the substrate electrode and the etching body, respectively. Rather, the pulse duty factor and the necessary peak pulse power are now effectively scaled in inverse proportion to one another.

On the whole, as a result of the high-frequency pulsing of the high-frequency power pulses, interference effects in the plasma-substrate electrode interaction are effectively suppressed, so that for a given frequency of the high-frequency generator, e.g. 13.56 MHz, and for a given, average high-frequency power coupled into the etching body, the ion energy and correspondingly the average ion current onto the etching body can be freely selected.

When P refers to the average high-frequency power, which is coupled into the etching body and is to be kept constant for a specific etching process, p refers to the peak pulse power and/or amplitude of the high-frequency power in a pulse, d refers to the pulse duty factor, u refers to the ion acceleration voltage corresponding to the energy of the ions impinging on the etching body, i refers to the pulsed ion current, and I refers to the temporal average value of the ion current, the following applies for the process according to the present invention:

$$p=\frac{P}{d} \quad u=\sqrt{X\frac{P}{d}}\propto\sqrt{\frac{1}{d}} \qquad i=\sqrt{\frac{1}{X}\frac{P}{d}} \qquad I=\sqrt{\frac{1}{X}Pd}\propto\sqrt{d}$$

In this context, it is assumed that plasma impedance X only changes minimally with the coupled high-frequency power and, therefore, approximates Ohm's law. In practice, due to the saturation effects of the ion current and to limited, available ion densities in the plasma, plasma impedance X increases even more as the coupled high-frequency power increases, thereby intensifying the described effect.

On the whole, the method according to the present invention, therefore, advantageously results in $u\propto\sqrt{\frac{1}{d}}$ applying for energy u of the ions impinging on the wafer in the case of a reduced duty cycle d (or analogously, in the case of a reduced mark-to-space ratio) and of correspondingly scaled-up peak pulse power p, i.e., constant average power P, while average current I behaves according to $I\propto\sqrt{d}$.

Thus, one can freely select via duty cycle parameters d for an equal power input whether a high ion energy having a correspondingly low average ion current or a low ion energy having a correspondingly high average ion current should be set. One is, therefore, afforded an additional degree of freedom in the etching process according to the present invention whose effect corresponds to an adjustability of the plasma impedance, and which can be used to widen the process window, e.g. for high-rate etching processes.

The method according to the present invention has the further significant advantage that, in addition to a high-frequency-pulsed high-frequency power, which is used for process stability in a wide process window and for suppressing

grass formation controllable via the characteristic quantities, ion energy, and average ion current, and which also leads to high etching rates, notching on the dielectric boundary surfaces can also be effectively suppressed by the additional low-frequency modulation of the high-frequency-pulsed high-frequency power.

This low-frequency modulation is based on the knowledge that relatively long times of typically more than 0.5 ms are necessary for reducing the charging effects on these dielectric boundary surfaces. The result is a frequency range for the low-frequency modulation of 10 Hz to 10000 Hz, preferably of 50 Hz to 1000 Hz.

The method according to the present invention is, therefore, suited in a particularly advantageous manner for a notching-resistant, high-rate etching process in the case of an increased process pressure of 20 Mbar to 300 Mbar, for example, and a high plasma power of up to 5000 watts.

Advantageous further refinements of the present invention result from the measures indicated in the dependent claims. Thus, it is particularly advantageous that also in the case of a small mark-to-space ratio of 1:9 through 1:19, for example, and correspondingly high peak pulse powers of the coupled high-frequency power pulses of 100 watts to 200 watts, a wide process window is retained with regard to the danger of grass forming.

It is further advantageous that conventional high-frequency generators can be operated in such a manner that a high-frequency pulsing of the coupled high-frequency power is possible in the form of rectangular pulses, the rise times of the clock pulse edges being less than 0.3 μs in the case of a carrier frequency of 13.56 MHz. As such, the method according to the present invention can be advantageously implemented

using commercially available generators, which, in some instances, may require only minor modifications.

Such a short rise time of the clock pulse edges is necessary to even be able to implement a high-frequency power pulsing having a frequency of 10 kHz to 500 kHz.

For the peak pulse power, i.e., the amplitude of the high-frequency power during a coupled high-frequency power pulse, further advantageous powers of 30 watts to 1200 watts can be used.

Furthermore, to produce the low-frequency modulation of the high-frequency-pulsed high-frequency power, two alternative possibilities, which are both simple to implement, are advantageously available. On the one hand, the high-frequency generator integrated in the generator unit and already clocked at a high frequency can, for example, additionally be directly switched on and off using low-frequency clocking via the generator's gate input.

On the other hand, there is also the possibility to use a low-frequency clock generator to control a high-frequency clock generator, which is integrated in the generator unit and modulates the actual carrier signal of the high-frequency generator, thereby causing the high-frequency pulsing of the high-frequency power. In this manner, the high-frequency clock generator is keyed in and blanked at a low frequency, which also correspondingly carries over to the coupled high-frequency power pulses.

Brief Description of the Drawings

The present invention is explained in greater detail by the drawings and the subsequent description. Figures 1a through 1c explain the pulses of the high-frequency power coupled into the etching body, Figure 2 shows a block diagram of an etching

system for implementing the etching method, and Figures 3a and 3b explain two alternative specific embodiments of the generator unit.

Exemplary Embodiments

Figure 2 shows a plasma etching system 5 principally known from DE 42 41 045 C2 or DE 197 06 682 A1, for implementing an anisotropic plasma etching method. For this purpose, a substrate electrode 12 is provided in an etching chamber 10 with an etching body 18, which is situated on the substrate electrode and is a silicon wafer in the explained example. Furthermore, substrate electrode 12 is electrically connected to a generator unit 30. Moreover, a resonator 20 is provided via which a plasma 14 is produced in etching chamber 10 in the region of a surfatron 16. The explained exemplary embodiment is, however, not limited to such a system configuration. In particular, an ICP plasma source (inductively coupled plasma) known per se or an ECR plasma source (electron cyclotron resonance) is also suitable for this purpose.

It is always only essential that a high-density plasma source produce a plasma 14, which is made of neutral radicals and electrically charged particles (ions), the ions being accelerated by a high-frequency power coupled into substrate electrode 12 and, above it, into etching body 18 in the direction of substrate electrode 12, which carries the etching body 18 to be processed, and impacting there in an almost vertical manner, so that the preferential direction of the incident ions results in a directed etching process.

With the exception of the design according to the present invention of generator unit 30, further details regarding etching system 5 known per se will not be provided because this is known to one skilled in the art.

Generator unit 30 has a commercially available high-frequency generator 33, a high-frequency clock generator 32, a low-frequency clock generator 31, and a so-called "matchbox" 34, i.e., an LC network. In this context, matchbox 34 is used in a known manner to adapt high-frequency generator 33 to the impedance of substrate electrode 12 and plasma 14, which is in contact with substrate electrode 12.

To ensure an effective mask selectivity (ratio of the etching rate of etching body 18 to the etching speed of a masking layer disposed thereon), a time-averaged high-frequency power of 1 watt to 30 watts is coupled into substrate electrode 12 via generator unit 30.

To produce the high-frequency-pulsed high-frequency power coupled into substrate electrode 12 and, above it, into etching body 18, it is first proposed that high-frequency generator 33 produce in generator unit 30 a high-frequency carrier signal 54 having a frequency of preferably 13.56 MHz and a power of 400 watts, for example. However, frequencies of 1 MHz to 50 MHz are also possible instead of the carrier signal frequency of 13.56 MGz. Furthermore, the power of high-frequency generator 33 can also be between 30 watts and 1200 watts. Powers between 50 watts and 500 watts are preferred.

In a first exemplary embodiment of the present invention, it is further provided in accordance with Figure 3a that, in addition to high-frequency generator 33 and matchbox 34, generator unit 30 has a high-frequency clock generator 32 known per se, which controls high-frequency generator 33 in such a manner that high-frequency generator 33 produces a high-frequency-pulsed high-frequency power. This is elucidated using Figures 1c and 1b. In detail, Figure 1c shows high-frequency carrier signal 54 of high-frequency generator 33 having a frequency of 13.56 MHz, for example, and a voltage amplitude corresponding to a power of 400 watts, for example.

According to Figure 1b, pulsing high-frequency generator 33 using high-frequency clock generator 32 produces high-frequency pulses 52, each of which is followed by a high-frequency pulse interval 53. Carrier signal 54 of high-frequency generator 33 is clocked by high-frequency clock generator 32 using a frequency of 10 kHz to 500 kHz, preferably 50 kHz to 200 kHz. The mark-to-space ratio of the high-frequency-pulsed high-frequency power according to Figure 1b is between 1:1 and 1:100. A ratio between 1:2 and 1:19 is especially preferred.

A high-frequency power of 1 watt to 100 watts, time-averaged over pulses and intervals is first produced by the selected mark-to-space ratio of the high-frequency-pulsed high-frequency power, starting from the produced power of high-frequency generator 30.

According to Figure 3a, generator unit 30 further has a low-frequency clock generator 31 known per se, which periodically switches high-frequency clock generator 32 on and off and/or clocks it. In this manner, the high-frequency-pulsed high-frequency power according to Figure 1b is also modulated at a low frequency. For this purpose, low-frequency clock generator 31 specifically clocks high-frequency clock generator 32 with a frequency of 10 Hz to 10000 Hz. Frequencies of 50 Hz to 1000 Hz are preferred. On the whole, clocking at a low frequency or modulating at a low frequency with the aid of low-frequency clock generator 31 causes the coupled, pulsed high-frequency power to be periodically switched on and off into substrate electrode 12 and, above it, into etching body 18. In this context, the mark-to-space ratio of the low-frequency clocking of low-frequency clock generator 31 according to Figure 1a, i.e., the ratio of low-frequency pulses 50 and low-frequency pulse intervals 51, is between 4:1 and 1:4. It has proven to be particularly advantageous when the mark-to-space ratio of the low-frequency clocking is between 1:2 and 2:1, e.g. 1:1.

As a result of the low-frequency clocking of the high-frequency-pulsed high-frequency power according to Figure 1b, the high-frequency power ultimately coupled into etching body 18 is reduced in accordance with the particular mark-to-space ratio (Figure 1a), so that a typical high-frequency power between 1 watt and 30 watts is ultimately coupled into etching body 18.

With respect to the envelope, high-frequency pulses 52 according to Figure 1b preferably at least approximate the form of a square-wave pulse, the rise time of the clock pulse edges of the square-wave pulses being less than 0.3 μs.

One can easily connect low-frequency clock generator 31 to a system control (not shown) and use the system control to control the average high-frequency power coupled into etching body 18 during the course of the implemented etching process. The mark-to-space ratio of the low-frequency clocking is particularly suitable for this purpose. The mark-to-space ratio of the high-frequency-pulsed high-frequency power according to Figure 1b is particularly suitable for optimizing the process with respect to the aforementioned grass formation. Of course, it is also possible to maintain the mark-to-space ratio of the low-frequency clocking, and to regulate the peak pulse power of the generator to control the average power.

As an alternative to Figure 3a, Figure 3b elucidates a specific embodiment of generator unit 30 for producing a high-frequency-pulsed high-frequency power, which modulates at a low frequency. For this purpose, according to Figure 3b, high-frequency generator 33 is first clocked at a high frequency, analogously to Figure 3a, via a high-frequency clock generator 32, so that it generates a high-frequency-pulsed high-frequency power according to Figure 1b. In contrast to Figure 3a, Figure 3b provides that low-frequency clock generator 31 does not control

high-frequency clock generator 32, but is directly connected to and also directly clocks high-frequency generator 33. A circuit arrangement according to Figure 3b can be particularly simply produced by connecting low-frequency clock generator 31 to the gate input of customary high-frequency generators 33, which are additionally clocked at a high frequency, e.g. via an internal clock generator or external clock generator 32. The remaining method parameters for implementing the etching method according to Figure 3b correspond to the method according to Figure 3a and Figures 1a through 1c, respectively.

In an overview, Figures 1a through 1c again clarify the high-frequency-pulsed high-frequency power coupled into etching body 18 and provided with a low-frequency modulation. For this purpose, Figure 1c, i.e., high-frequency carrier signal 54 of high-frequency generator 33, is first used as a baseline. According to Figure 1b, this carrier signal 54 is subdivided by high-frequency clock generator 32 into high-frequency pulses 52 and high-frequency pulse intervals 53. In this context, high-frequency pulses 52 are ideally at least approximately in the form of square-wave pulses (envelope) and are formed by carrier signal 54. Figure 1a then clarifies how the high-frequency-pulsed high-frequency power coupled into etching body 18 is clocked and/or modulated at a low frequency with the aid of low-frequency clock generator 31. For this purpose, a plurality of high-frequency pulses 52 and high-frequency pulse intervals 53, respectively, are combined into low-frequency pulses 50, which are then each followed by a low-frequency pulse interval 51. As the envelope, low-frequency pulses 50 are preferably also in the form or square-wave pulses. The signal according to Figure 1a is then coupled into etching body 18 via substrate electrode 12 as high-frequency power.